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Radiation Characteristics of the TACAMO-IV-A Airborne VLF Transmitting System

[Unclassified Title]

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Communications Sciences Division

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Radiation Characteristics of the TACAMO-IV-A Airborne VLF Transmitting System
[Unclassified Title]

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The Naval Research Laboratory and other Navy laboratories cooperated to conduct an investigation to determine the vertical effective radiated power (VERP) of the TACAMO-IV-A airborne VLF transmitting system. The mobile nature of this system required special techniques for this investigation. A series of comparison tests was made in which the TACAMO-IV-A was located near the ground-based transmitting station NAA at Cutler, Maine, and operated at 18.2 kHz, a frequency close to that of NAA (17.8 kHz). Simultaneous field-strength measurements of special transmissions from the two transmitting systems were made at great distances. Precise measurements of the NAA radiated power and a comparison of the received field strengths were used to determine the TACAMO-IV-A VERP.

This report is intended as an analysis of the results of the VERP measurements with particular emphasis on its application to the prediction of communication coverage to surface or subsurface receiving systems. The results show that the system design objective of an average VERP of 100 kW was obtained. However, the optimum communications from the TACAMO systems are achieved while flying in a tight, 2- to 3-minute-orbit pattern. Even under optimum conditions the received field strengths from the TACAMO-IV-A and other TACAMO systems have an orbit-produced periodic fluctuation of 3 dB. Since this fluctuation occurs at least once each orbit, the effective VERP for communication coverage predictions for the TACAMO-IV-A is 71 kW, which is 1.5 dB below the average 100 kW.

INTRODUCTION

In March 1970 the Naval Research Laboratory (NRL) took part in a joint program with the Naval Air Development Center (NADC), the Naval Air Test Center (NATC), and the Lockheed-Georgia Company to measure the vertical effective radiated power (VERP) of the TACAMO-IV-A system. The TACAMO-IV-A is an airborne, very-low-frequency (VLF) transmitting facility developed as a feasibility model for the Navy by the Lockheed-Georgia Company. The development of the TACAMO-IV-B system is now under contract.

Since the TACAMO-IV-A is an airborne system employing thousands of feet of trailing wire as an antenna, the measurement of its VERP requires special techniques other than those used for such measurements for a ground-based VLF transmitting station. The techniques employed will be discussed more fully later, but basically they consist of a series of measurements whereby the field strengths of the TACAMO-IV-A transmissions and those from the VLF transmitting station (NAA) at Cutler, Maine, were measured at distant sites. During the period of these comparison measurements, the TACAMO-IV-A was operated near the NAA transmitter, and at a frequency (18.2 kHz) close to that of NAA (17.8 kHz). The radiated power of NAA was accurately measured, and through the comparison of the field strengths of the TACAMO-IV-A and

NRL Problem R07-22; NAVELECSYSCOM, SPECOM, PME-117; Project X1508 Task D. This is the final report on one phase of this problem; work continues on other phases.

NAA at distant points, the VERP of the TACAMO-IV-A was determined.

The VERP measurement program, a part of the "Proof of Performance" evaluation of the TACAMO-IV-A system, was carried out by making field-strength comparison measurements at Rota, Spain; Roosevelt Roads, Puerto Rico; Lajes, Azores; and Marietta, Georgia, by NRL, NADC, NATC, and Lockheed-Georgia, respectively. In addition, NRL made measurements in the vicinity of NAA to determine its radiated power and continuously recorded all the special TACAMO-IV-A and NAA test transmissions nearby at Ellsworth, Maine. In an effort to gain more information on the characteristics of the transmissions from this airborne transmitting facility, arrangements were made to have data recorded in Buffalo, New York, by the Cornell Aeronautical Laboratory, in Boulder, Colorado, by the Westinghouse Georesearch Laboratory, and in San Diego, California, by the Naval Electronics Laboratory Center. In addition, some of the test transmissions were recorded near Washington, D.C., by NRL.

The Navy Long Wave Propagation Center, maintained by NRL, is responsible for predicting the communications reliability of all Navy VLF transmitting facilities. This report is intended as an analysis of the TACAMO-IV-A VERP measurements with particular emphasis on the application of the results to the prediction of communication coverage from this airborne transmitting facility.

BACKGROUND

The TACAMO airborne VLF transmitting systems have been in operational use by the Navy for several years. The fourth generation of these systems, TACAMO-IV-A, was developed to demonstrate, among other things, the feasibility of radiating about 100 kW from such an airborne system. The radiated power from previous TACAMO systems was roughly 10 kW. The previous versions employed a single, half-wavelength, trailing-wire antenna, whereas, the TACAMO-IV-A had a several-thousand-foot trailing-wire counterpoise in addition to the antenna wire.

(U) When transmitting, the TACAMO is usually flown in a tight-orbit pattern so that the trailing-wire antenna will assume a configuration with the maximum degree of verticality. In this manner the VERP is maximized along with the communication-coverage range to a ground-based or submerged receiving system. Since the TACAMO antenna is elevated and has at least some degree of horizontal component, horizontally polarized field components are generated and propagate to great distances. Basically the TACAMO antenna is a complex elevated dipole. The fields from elevated dipole antennas have been treated theoretically by Wait (1), by Galejs (2-4), by Pappert (5), and by Pappert and Bickel (6).

Kelly's (7) theoretical treatment of the elevated dipole and its associated fields was more directly applicable to the orbiting TACAMO situation. In a classified report, Kelly (8) compared his theoretical results with the results from many experimental investigations of the fields from several TACAMO systems. In this latter work, he shows that the field strengths from the TACAMO can exhibit orbit-related variations as large as 30 dB if a high degree of antenna verticality is not maintained. Kelly states that as the antenna goes around a circular path (orbiting TACAMO), the interference between the VLF waveguide modes generated by the vertical and horizontal components of the inclined antenna cause these periodic field-strength variations. When the horizontal component of the antenna is small (high percentage of verticality), the interference effects (field-strength variations) are small. The magnitude and sense (whether increasing or decreasing) of these orbit-related periodic variations are a function of the distance and bearing of the receiver from the transmitter. The received field strength may have one or two cycles of variation during each orbit, depending on the distance as related to the modal interference pattern of the resultant field propagated from the TACAMO. Also, aerodynamic forces on the trailing-wire antenna cause it to rise and fall (yo-yo action) during each orbit. This yo-yoing produces an oscillation in the inclination angle of the antenna, which in turn produces an additional periodic variation that can either enhance or reduce the received field-strength variations caused by purely orbital motion. The resultant variations depend on bearing and range, again related to the modal interference pattern of the fields.

(U) The yo-yo action of the TACAMO antenna is present whether the aircraft is flown in an optimum orbiting configuration (maximum degree of antenna verticality) or in a wide orbit. However, when operated in this optimum configuration, the TACAMO field strengths show a comparatively small (about 3 dB) variation per orbit. Experimental data indicate that this variation is produced by the yo-yoing, which results in a variation in the effective vertical length of the antenna while increasing the horizontal component only slightly. The above information, concerning the large variations that may occur when the orbiting of the TACAMO is such that the horizontal component becomes appreciable, is furnished only to provide background information concerning the electromagnetic fields propagated from the TACAMO antenna.

(U) It should be noted that during the multiple test flights for this VERP measurement program, it was repeatedly demonstrated that the TACAMO-IV-A could be flown in an optimum orbiting configuration for which the total excursion of the field-strength variations was about 3 dB per orbit. It should be further noted that the weather conditions during this period were variable and not always ideal.

The results of this investigation did substantiate the theoretical work by Kelly (7) concerning the distance and bearing dependence of the field-strength variations, although this statement is in conflict with the conclusions drawn by Owen and Burns (9).

INSTRUMENTATION

The method of measuring the TACAMO-IV-A radiated power by which the field strengths were compared with those from NAA at distant sites, did not require precise, absolute, field-strength measurement capabilities at these sites. It was necessary only that the relative accuracy of the two sets of measurements (TACAMO-IV-A and NAA) be as precise as possible. The near-field measurements of NAA, which were used to determine its radiated power, were made employing equipment and techniques which provided for measurement accuracies within 0.2 dB.

At the distant monitoring sites, conventional VLF field-strength-measuring equipments with loop antennas were used. External calibration systems were employed, however, providing for an overall accuracy capability for absolute field measurements of about 0.5 dB. The techniques used by NRL at the Rota site resulted in a relative accuracy of the two measurements of about 0.3 dB. The signal-to-noise ratios for both the TACAMO-IV-A and NAA transmissions (18.2 and 17.8 kHz respectively) were sufficiently high at all sites so that the measurement accuracy was not affected by the noise.

PROCEDURE

(U) The power radiated by the conventional, ground-based, VLF transmitting stations is determined through a series of field-strength measurements of the ground wave at various distances and bearings from the antenna within the range where the field strength varies inversely with distance. In the portion of the VLF spectrum between 15 and 30 kHz, these distances range between about 10 and 75 km. Closer than 10 km the induction field component must be considered if a magnetic sensor is used, and if an electric sensor is used, both the induction and electrostatic field components may be significant. Beyond 75 to 90 km the contribution of the sky wave must be considered, and this normally is not known to a sufficient accuracy. The use of multiple field-strength measurements at various distances and bearings is required to average out local anomalies. These techniques are treated in detail by Garner and Raudenbush (10). The techniques and results of radiated-power measurements for the VLF transmitting station NWC at North West Cape, Australia, are given by Garner, Raudenbush, and Brookes (11).

(U) The mobile nature of TACAMO requires special techniques for the measurement of its radiated power. The techniques discussed in Ref. 10 for short ranges require precise measurements of field strength and distance from the transmitting antenna. This would be virtually impossible to do for the TACAMO system. Since it was desired to determine the VERP from an orbiting TACAMO, as applied to communications to ground-based or submerged receiving systems, a comparison of the TACAMO fields with those from a known, ground-based VLF transmitter appeared to offer the best meaningful results.

The VLF transmitting station NAA at Cutler, Maine, is located along the Atlantic coast, and it was therefore possible to orbit the TACAMO-IV-A over seawater yet be very close to a transmitting station that could be used for comparison. The two transmitters not only had to be located close together in space, but, to avoid differences in propagation effects, had to be operated at the same, or nearly the same, frequency. To allow for simultaneous comparison, the transmitters were operated at frequencies (17.8 kHz for NAA and 18.2 kHz for TACAMO-IV-A) as close as practical, considering the selectivity of the receiving equipment. Three primary sites for recording the field-strength data used in determining the TACAMO-IV-A VERP were operated at Rota, Spain; Lajes, Azores; and Roosevelt Roads, Puerto Rico. The propagation paths to these sites were entirely over seawater, with Rota and Lajes being at different distances but very nearly along the same great-circle path, which was at a bearing approximately 90° from Roosevelt Roads. The two paths, differing by about 90°, were chosen to gain more knowledge concerning the directional effects discussed by Kelly (7,8). To aid in this facet of the investigation, other data-recording sites were operated as mentioned previously, and the TACAMO-IV-A occasionally was flown in a wide orbit (10° bank) in addition to the tight, optimum orbit. Also, each time the aircraft passed through a 00-degree true heading the TACAMO-IV-A transmissions were shifted 200 Hz so as to provide a synchronizing mark on all field-strength data recordings (strip charts). All the data-recording sites used in this program and their distances and bearings to the TACAMO-IV-A orbit center are given in Table 1.

The VERP of the TACAMO-IV-A was determined by measuring simultaneously the field strengths of special transmissions from NAA and TACAMO-IV-A. Then knowing the radiated power of NAA from near-field measurements, the TACAMO-IV-A radiated power could be calculated, since the dB relation of the received field strengths of the two transmissions is the same as that of their radiated powers.

The series of TACAMO-IV-A test transmissions for establishing the VERP consisted of 20-minute continuous transmissions (18.2 kHz) while orbiting. Approximately midway during these tests, NAA transmitted (17.8 kHz) continuously for about 3 minutes. The test transmission periods were centered around noon for the propagation paths to Spain and Puerto Rico, so the propagation conditions during these 20-minute periods were quite stable for most monitoring sites. The propagation paths to Boulder, Colorado, and San Diego, California, however, were in sunrise transition, and consequently the propagation conditions were variable.

Table 1
Distances and Bearings of Data-Recording Sites From TACAMO-IV-A Orbiting Near Cutler, Maine

Site Location	Distance (km)	Bearing (degrees true)
Ellsworth, Maine	96 (approx.)	326 (approx.)
Rota, Spain	5150	76
Lajes, Azores	3290	86
Roosevelt Roads, Puerto Rico	2850	175
Buffalo, New York	940	262
Washington, D.C.	950	238
Boulder, Colorado	3080	276
San Diego, California	4420	272

(U) The instrumentation, calibration techniques, and ambient-noise levels at all monitor sites were not uniform. Consequently the VERP values presented here were derived from the data recorded only at Rota, Roosevelt Roads, and San Diego, which were considered to be the most reliable data. Owen and Burns (9) used data from all the sites, but there is no significant difference between their average VERP and that given here.

The stable propagation conditions for the Rota and Roosevelt Roads paths allowed for an averaging of the TACAMO-IV-A transmissions over the 20-minute period and a comparison with the 3-minute NAA transmissions. However, for the San Diego data the TACAMO-IV-A transmissions for only a couple of orbits, centered around the 3-minute NAA transmissions, were used for comparison, because of ionospheric transition effects.

RESULTS

(U) The TACAMO-IV-A test transmissions on March 6, 1970, from 1442 to 1536 UT were recorded at most of the monitor sites and provide the best example of the characteristics of the received field strengths for both the tight (optimum) and wide (10° bank) orbiting conditions. Figure 1 shows the relative field strengths received at the various sites while the aircraft was flying in tight orbits (1442 to 1505 UT). It can be seen that the oscillatory pattern of the received field strength is virtually the same at all sites from Ellsworth, Maine (within line of sight at 96 km), to Rota, Spain (5150 km). This similarity of the fields at all sites, whereby the excursions of the oscillations and the occurrence of the maxima and minima with respect to the heading of the aircraft are nearly the same, indicate that these oscillations in the fields are due primarily to the yo-yoing of the TACAMO-IV-A antenna. That is, the vertical component, and consequently the effective height, of the antenna is oscillating in synchronism with the aircraft orbits. This yo-yo action results in a fluctuation of the VERP.

(U) Close examination of the relative field-strength patterns presented in Fig. 1 reveals that there are slight differences in the total amplitude change per orbit from one site to another. The Washington, D.C., data show the smallest excursion, about 1.5 dB, and the Lajes data have the largest, 3.5 dB. These slight differences are due to the effect of the small but obviously significant horizontal component of the antenna even when operating in the optimum, tight orbit. The horizontal component of the antenna, although relatively small, varies as the antenna yo-yos. The slight deviation in the occurrence of the maxima and minima with respect to the aircraft heading as shown for any one site could be due to changes in aerodynamic conditions, or more likely, to errors in the 00-degree heading marks.

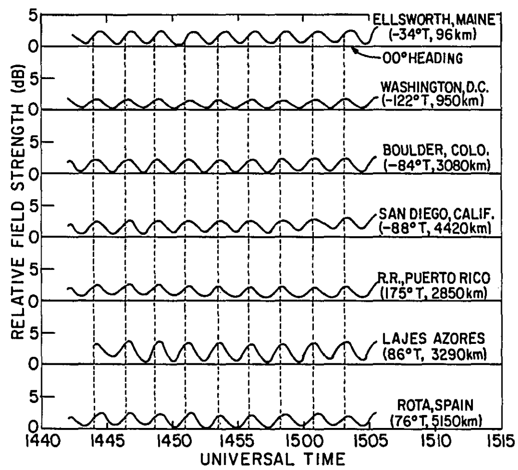

Fig. 1 (U) – Relative field strength of TACAMO-IV-A transmissions (18.2 kHz) on March 6, 1970, while flying a tight-orbit pattern. The true bearing and distance of each receiving site from the TACAMO are given.

(U) The field-strength variations of approximately 3 dB shown in Fig. 1, which were recorded during what is considered to be optimum operating conditions for the TACAMO systems for communication to surface or subsurface receiving points, are about the minimum that can be expected under average operating conditions. Operating the TACAMO in straight-and-level flight could produce a more steady, but considerably reduced, received field strength. The difference in received field strength at a surface or subsurface point is roughly 8 to 10 dB higher when the TACAMO is in a tight orbit than when it is in straight-and-level flight.

(U) When the TACAMO-IV-A was operating in a wide orbit (10° bank), the antenna had less verticality and consequently more horizontal component. Examples of the variations in received field strength under these conditions are shown in Fig. 2. The variation patterns discussed by Kelly (7,8) under such wide-orbit conditions are clearly visible. That is, the magnitude of the oscillations and whether there are one or two oscillations per orbit are shown to be both distance and bearing dependent. The 00-degree heading marks show that one wide orbit requires about 5.5 minutes, whereas the tight orbit was completed in about 2.5 minutes. The most severe oscillations are observed at Ellsworth, but it must be remembered that this is within line of sight. The path bearings to Buffalo and Washington differ by only 24°, and the distances are virtually the same. The field-strength oscillations at these two medium-distance sites are nearly identical, with one oscillation per orbit and with the same sense (maxima and minima occur at the same time). The oscillations at all other receiving sites shown in Fig. 2 exhibit two cycles per orbit. The Boulder and San Diego sites are approximately along the same great-circle path through the TACAMO location, as are the Lajes and Rota sites. The bearings of these two pairs of sites differ by roughly 180°. The field-strength oscillations at all four of these sites are very similar and have the same sense. The shape of the oscillations at Roosevelt Roads, Puerto Rico, are very similar to those at these other four sites except that they have the opposite sense. That is, the field strength at Roosevelt Roads is increasing when the others are decreasing, and vice versa.

(U) The received-field-strength patterns shown in Fig. 2 are, in general, in agreement with the theoretical model of Kelly (7), although he shows a two-cycle-per-orbit oscillation occurring only at a modal interference null. The phasor relationship between the vertically and horizontally polarized field components which give rise to the double cycle could occur as well, however, at any distance, as found by Rhoads (12) during an extensive TACAMO propagation investigation carried out in March and April 1971. During this investigation, propagation data from an orbiting TACAMO were recorded at several ground-based sites along a radial path and aboard a receiving aircraft flying over this same radial path from the TACAMO.

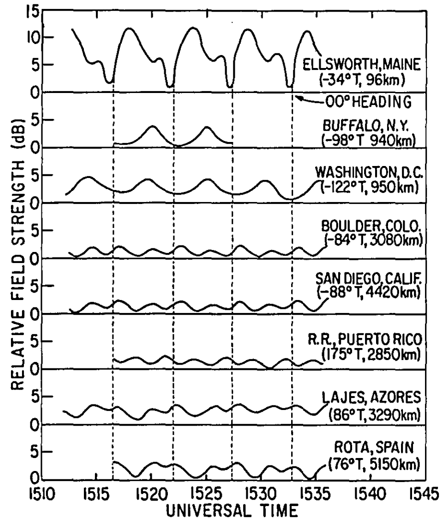

Fig. 2 (U) — Relative field strength of TACAMO-IV-A transmissions (18.2 kHz) on March 6, 1970, while flying a wide-orbit (10° bank) pattern. The true bearing and distance of each receiving site from the TACAMO are given.

During one test of this recent investigation, when the TACAMO was flown in wide orbits, the airborne and ground-site received field strengths continuously showed two-cycle oscillations per orbit over a distance from 1200 to 2800 km. This investigation was carried out to more fully study the extremeties of the fading characteristics of the TACAMO field strengths under both optimum and poor orbiting conditions, and to develop techniques to insure operation of the TACAMO systems in optimum-orbit patterns. The results of this investigation are currently being analyzed and will be reported on in the near future.

The data from the March 6, 1970, tight-orbit test presented in Fig. 1 for the three sites used for determining the VERP and the Ellsworth data are replotted in Fig. 3 in absolute field strength. Also shown are the absolute field strength of the NAA test transmission as received at each of these sites and the corresponding NAA radiated power as measured at Ellsworth and correlated with many near-field measurements used to establish the radiated power and radiation resistance of NAA. The Ellsworth data shown in Fig. 3 cannot be used for establishing the TACAMO-IV-A VERP, since the distances to the TACAMO and NAA were not exactly equal. At such close ranges

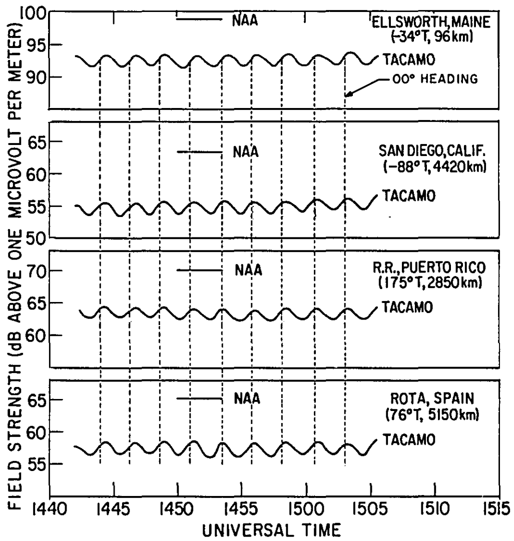

Fig. 3 — Comparison of TACAMO-IV-A and NAA transmissions (18.2 and 17.8 kHz respectively) on March 6, 1970, for a TACAMO flying in a tight-orbit pattern. The NAA radiated power during this test transmission was 524 kW or 27.2 dB above 1 kW. The true bearing and distance of each receiving site from the TACAMO are given.

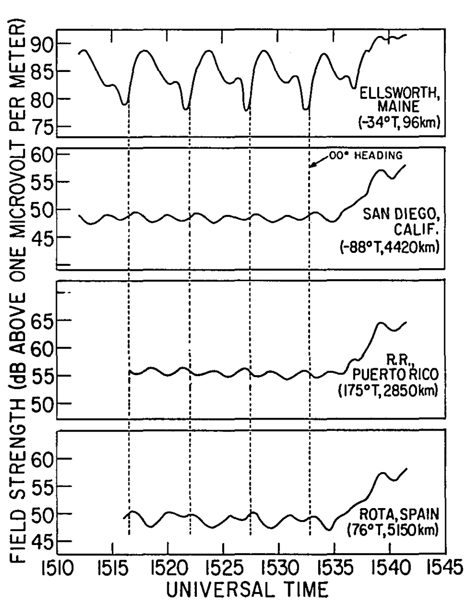

Fig. 4 — Field strengths of TACAMO-IV-A transmissions (18.2 kHz) on March 6, 1970, while flying a wide-orbit pattern. After 1535 UT the TACAMO changed from a wide orbit to a tight orbit. The true bearing and distance of each receiving site from the TACAMO are given.

even small differences in distance would have an appreciable effect on the apparent radiated power.

(U) The wide-orbit (10° bank) data recorded at four sites on March 6, 1970, previously shown in Fig. 2 are replotted in absolute field strength in Fig. 4. In this illustration a small sample of data after 1535 UT, when the TACAMO-IV-A changed its flight pattern from a wide to a tight orbit, has been included. The data between 1539 and 1542 UT are for one tight orbit and illustrate the approximate 8-dB gain in radiated power for tight-orbit operation over that for wide-orbit operation.

Figure 5 shows a comparison of the TACAMO-IV-A and NAA data recorded at three monitor sites for eight test periods. These data are plotted in radiated power referenced to the NAA radiated power as determined by its near-field measurements. The TACAMO-IV-A data presented are, in general, the average of the maxima and minima over the period of the test transmission, usually about 20 minutes. However, the San Diego data are averaged over a much shorter period when the tests periods were during the sunrise transition, since the NAA test transmissions were for only 3 minutes. It can be seen that the radiated power of NAA varied somewhat from day to day. This was partially due to transmitter problems, but on March 4 the reduction was due to operation on only half of the NAA system, as is periodically done for maintenance.

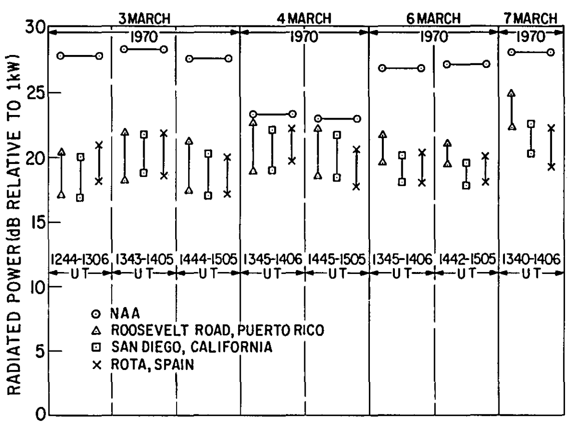

Fig. 5 — Radiated power of NAA (17.8 kHz), determined from near-field measurements, and of TACAMO-IV-A (18.2 kHz) in a tight-orbit pattern referenced to NAA through simultaneous field strength at three monitor sites.

These changes in NAA radiated power had no effect on the TACAMO-IV-A VERP measurement, since the NAA radiated power was continuously measured locally.

The data for the three sites and eight test periods presented in Fig. 5 indicate an average VERP for the TACAMO-IV-A at 18.2 kHz of 20 dB above 1 kW, which is 100 kW. This was the design objective for the TACAMO-IV-A.

CONCLUSION

(U) The data presented in Fig. 1 and 3, and the other data recorded during the eight tests conducted on four days in March 1970 at 18.2 kHz, show that under optimum, tight-orbit flight patterns the received field strengths of TACAMO-IV-A transmissions have an orbit-produced periodic variation of about 3 dB. These oscillations are produced primarily by the yo-yoing of the TACAMO-IV-A antenna, resulting in a periodic variation in the VERP, which must be considered in establishing the effective VERP for predicting the communications coverage from the TACAMO systems.

The investigation reported here established that the TACAMO-IV-A was capable of maintaining an *average* VERP of 100 kW at 18.2 kHz. Since the VERP varies approximately sinusoidally by 1.5 dB about this average 100 kW during each 2- to 3-minute orbit, this average VERP is not a meaningful value for use in communications-coverage predictions. Assuming an average, tight-orbiting-TACAMO VERP of 100 kW, the effective communications VERP for 18.2 kHz is approximately 71 kW.

When the TACAMO system is flown in a wide orbit (10° bank), the orbit-produced periodic variations may have one or two cycles per orbit, and the amplitude of these variations may be as much as 15 to 25 dB, as shown by Kelly (8) and Rhoads (12), and are both bearing and distance dependent. The average VERP when in the wide-orbit pattern is roughly 8 dB lower than for the tight-orbit situation, as demonstrated here and by Rhoads (12). When flown on a straight-and-level course, even at slow speeds to produce the maximum degree of verticality, the VERP reduction reported by Rhoads (12) is about the same as for the wide-orbit situation, but in some instances it is as much as 10 dB.

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Department of the Navy Naval Electronic Systems Command Washington, D.C. 20360

13. ABSTRACT

(C) The Naval Research Laboratory and other Navy laboratories cooperated to conduct an investigation to determine the vertical effective radiated power (VERP) of the TACAMO-IV-A airborne VLF transmitting system. The mobile nature of this system required special techniques for this investigation. A series of comparison tests was made in which the TACAMO-IV-A was located near the ground-based transmitting station NAA at Cutler, Maine, and operated at 18.2 kHz, a frequency close to that of NAA (17.8 kHz). Simultaneous field-strength measurements of special transmissions from the two transmitting systems were made at great distances. Precise measurements of the NAA radiated power and a comparison of the received field strengths were used to determine the TACAMO-IV-A VERP.

(C) This report is intended as an analysis of the results of the VERP measurements with particular emphasis on its application to the prediction of communication coverage to surface or subsurface receiving systems. The results show that the system design objective of an average VERP of 100 kW was obtained. However, optimum communications from the TACAMO systems are achieved while flying in a tight, 2- to 3-minute-orbit pattern. Even under optimum conditions the received field strengths from the TACAMO-IV-A and other TACAMO systems have an orbit-produced periodic fluctuation of 3 dB. Since this fluctuation occurs at least once each orbit, the effective VERP for communication coverage predictions for the TACAMO-IV-A is 71 kW, which is 1.5 dB below the average 100 kW.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
VLF communications VLF airborne transmitting systems VLF transmitter radiated power						

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